

Mississippi River Updated Stage-Frequency Backwater Areas

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Abstract

Stage-frequency profiles for the Mississippi River were developed from Hastings, Minnesota downstream to Guttenberg, Iowa in the St. Paul District using updated flow-frequency values. Period of record inflow hydrographs were routed with a current condition unsteady flow model to determine a stage-discharge relationship at each cross section using the annual maximum values. A statistical analysis combines the flow-frequency with stage-discharge to determine stage-frequency values at each individual cross section. In backwater areas such as exists just upstream of the Wisconsin, River, the methodology produced jumps in the computed water surface profiles requiring an alternative procedure. The stage upstream of the mouth of a major tributary is a function of both the upstream flow on the main stem and the stage downstream of the tributary. The downstream stage on the tributary is a function of the total flow upstream on the main stem plus the coincidental tributary flow. The problem and alternative procedure are discussed as well as the stage frequency results.

Introduction

Congress tasked the Corps of Engineers to conduct a comprehensive, system-wide study to assess flood control and floodplain management practices in the areas that were flooded after the flood of 1993. That resulted in the Floodplain Management Assessment study (FPMA) (USACE, 1995). The study involved the following Corps of Engineer Districts: St. Paul, Rock Island, and St. Louis on the Mississippi River, and Omaha and Kansas City on the Missouri River. Each District developed independent unsteady flow UNET models. UNET is a one-dimensional unsteady open channel flow simulation model. The UNET simulation models were developed further for the Mississippi River Basin Modeling System and the Upper Mississippi Flow Frequency Study. Additional stage frequency software developed for the Flow Frequency Study is used in combination with the UNET period of record output for determining stage frequency profiles. The recommendation for the Mississippi River presented in this paper are a result of a joint effort between the Rock Island and St. Paul District Corps of Engineers and Dr. David Goldman, Consultant for the Upper Mississippi River System Flow Frequency Study.

Geographic Coverage. The area modeled using UNET is extensive - from Anoka, MN to Thebes on the Mississippi River, from Gavins Point Dam on the Missouri River to St. Louis (confluence with the Mississippi) and from Lockport Lock & Dam to Grafton on the Illinois River. Portions of numerous smaller tributaries in the Basin are also modeled as unsteady flow routing reaches. The area of interest for the St. Paul District for the Mississippi River in the vicinity of the Wisconsin River is shown on **Figures 1 and 2**. Impacts from the tributary analysis influence stages on the Mississippi River downstream to Dubuque, Iowa which is at River Mile 579.3. Dubuque, Iowa is within the Rock Island District.

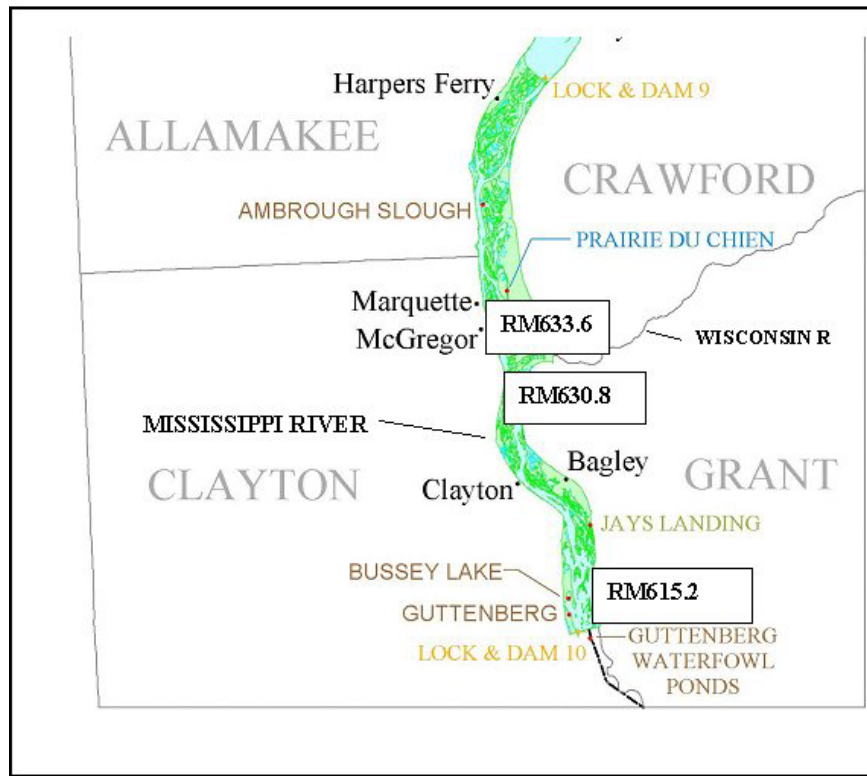


Figure 2. Area Map of the Mississippi River in the vicinity of the Wisconsin River

BASIN DESCRIPTION

Watershed Characteristics

This study encompasses the entire Mississippi River watershed area of about 714,000 square miles above the mouth of the Ohio River at Cairo, Illinois. The portion of the study area within the St. Paul District includes about 79,400 square miles above Lock and Dam 10 at river mile 615.1 miles above the mouth of the Ohio River at Cairo, Illinois. The area of the Upper Mississippi River within the St. Paul District is comprised of six major hydrologic units representing a diverse landscape and wide range of hydrologic conditions. The principal drainage units displayed in **Figure 3** include the Headwaters of the Mississippi River area above St. Paul, Minnesota River, St. Croix River, Chippewa River, the Black and Root River drainage unit and the Wisconsin River.

Watershed characteristics vary considerably from the Mississippi River's origin at Lake Itasca in the headwaters area, which is dominated by lakes and forest to the prairie pothole region of the Minnesota River basin, which has been extensively drained and is dominated by agriculture. Mean annual runoff varies from about 3.6 inches in the western portion of the Minnesota River basin to about 9.5 inches in the St. Croix River basin.

Flood Frequency Distribution Estimation Method

An investigation of flood frequency distribution estimation methods resulted in a recommendation by the Technical and Interagency Advisory Groups (TAG and IAG) to use the basic methodology described in Bulletin 17B for obtaining at-site estimates of flood distributions for the Upper Mississippi Basin Flood Frequency Study. The Bulletin recommends the log-Pearson III distribution with method of moments to estimate flood quantiles (e.g., the 1% chance annual peak flow). The TAG and IAG also recommended regionalization of the flood statistics to obtain consistent flood quantile estimates. Regional shape estimation also involves estimating average skew values for statistically homogenous regions and substituting this average value for the at-site value when estimating the flood-frequency distribution.

Flood regions may be defined by the confluence of major rivers (e.g., Kansas and Missouri, Illinois and Mississippi, Mississippi and Missouri), a change in climatology or some other feature that is manifested in the observed flow series. A statistical approach is proposed by the Technical Advisory Group (TAG) to obtain regional boundaries (see Hydrologic Engineering Center, 2000). The approach taken identifies boundaries based on channel characteristics, statistical variation of flood characteristics, and climate across the study area. Once regions with statistically similar flood characteristics were defined, a regional skew coefficient (a regional shape parameter) is obtained as an average of the at-site gage estimates within the region. The flood frequency distribution is computed from the at-site mean and standard deviation combined with the regional skew coefficient used as the adopted skew coefficient. Flood distributions in between gages are obtained by a linear smoothing relationship of the mean flow and the standard deviation with drainage area.

The final McGregor mean and standard deviation are interpolated from the linear relationship between Winona and Dubuque. Other regression methods were considered to define a 'best fit' relationship between the observed data listed in **Table 1**, but the TAG and IAG recommended linear interpolation. The plots displayed in **Figure 4** display the linear variation estimated for the mean and standard deviation between gages that are used to determine regionalized statistics for McGregor and other points of interest between the gauging stations. The data at Clinton and Keokuk are used to ensure consistency with the relationships in the Rock Island District. The final means and standard deviations to be used in the development of flood probabilities within the St. Paul District are listed in **Table 2**.

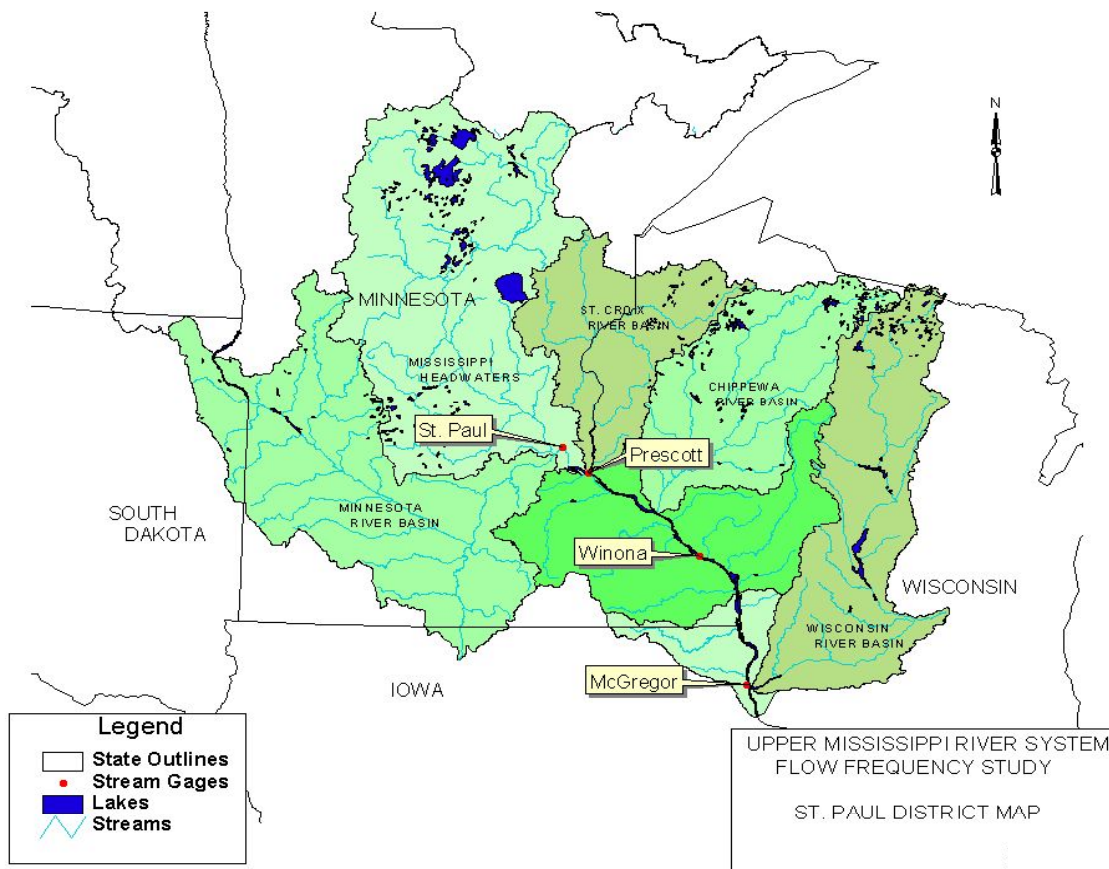


Figure 3. Principal Drainage Area Units for the Mississippi River - St. Paul District

**Table 1. At-Site (Un-Regulated) Statistics for St. Paul District Gages
Period of Record (1898-1998)**

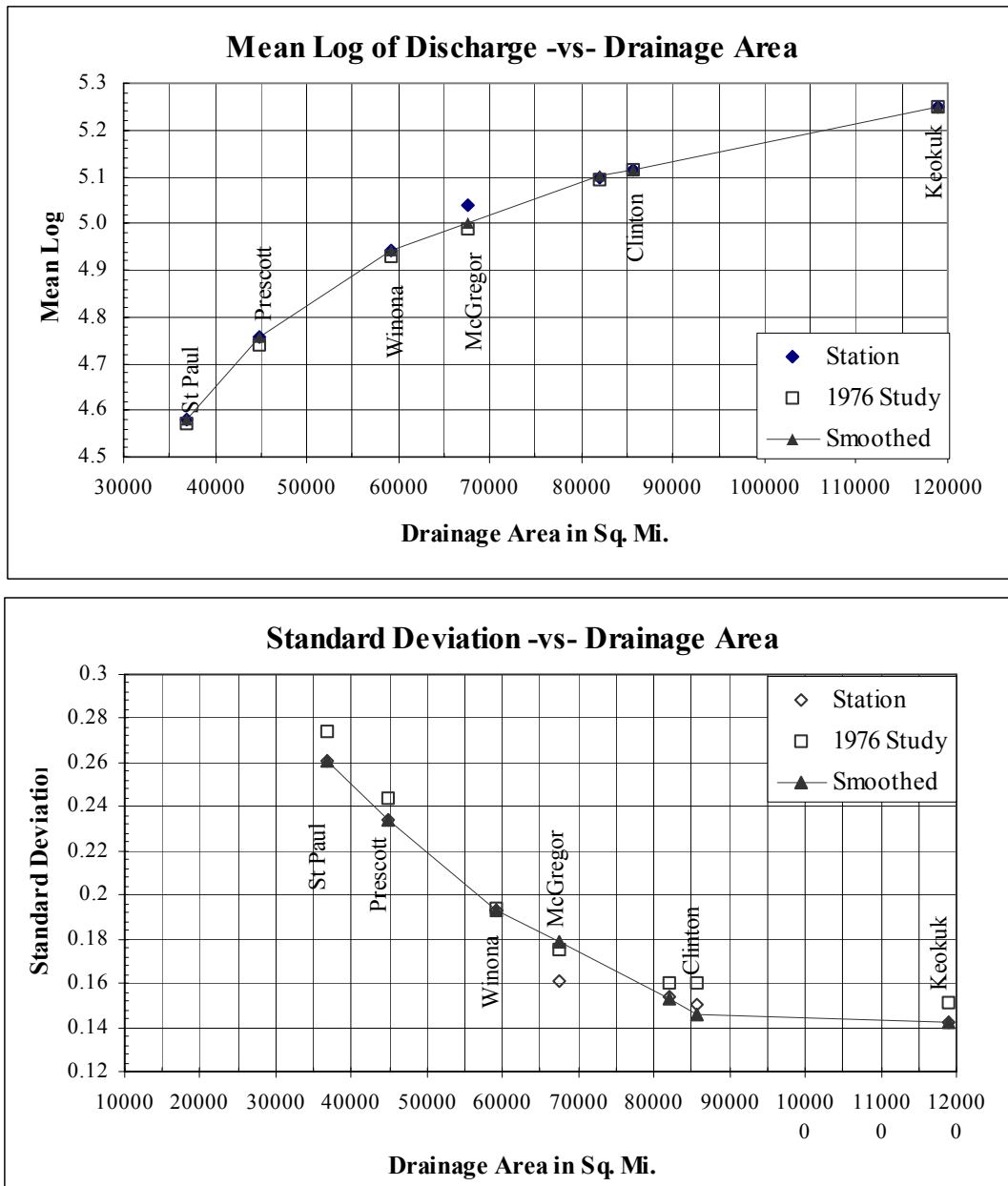
River Mile	Station	Drainage Area	Mean	Standard Deviation
839.3	St Paul	36800	4.581	0.261
811.4	Prescott	44800	4.756	0.234
725.7	Winona	59200	4.944	0.193
633.4	McGregor (1937-1998)	67500	5.038	0.161
518.2	Clinton ¹	85600	5.114	0.146
364.0	Keokuk ¹	119000	5.248	0.142

1. Clinton and Keokuk gages are located in Rock Island District, but are listed since they are included in St. Paul District smoothing analysis. The McGregor statistics are for a shorter record from 1937-1998.

**Table 2. Final Regionalized Statistics for St. Paul District Gages
Period of Record (1898-1998)**

River Mile	Station	Drainage Area	Mean	Standard Deviation
839.3	St Paul	36800	4.581	0.261
811.4	Prescott	44800	4.756	0.234
725.7	Winona	59200	4.944	0.193
633.4	McGregor	67500	5.000	0.178

Figure 4. Smoothing at Site Statistics with Drainage Area



NOTE: Station statistics are based on period of record (POR) from 1898-1998, with exception of McGregor station where POR is from 1937-1998. The 1976 study statistics at St Paul is based on a POR of 1862-1976. The 1976 statistics for Clinton are based on POR from 1874-1975. All other 1976 study statistics are adjusted based on correlation with longer-term stations. Smoothed relationship is a linear fit between the station statistics at St Paul, Prescott, Winona, Dubuque, Clinton and Keokuk.

Stage Frequency Methodology

The methodology adopted for the Flow Frequency Study consists of a period of record analysis using UNET for determining annual peak stage and discharge simulated values. Once the simulated values are determined, additional stage frequency software developed by Dr. David Goldman is utilized for determining stage frequency results at each cross-section.

Period of Record UNET analysis

The observed period of record UNET runs are for the period from 1940-2001. In the St. Paul District, the curves at many cross-sections don't extend far enough for even the 0.5 percent chance flood event. The Flow Frequency Study required the determination of stage frequency profiles for events up to and including the 0.2 percent chance flood event. For the simulations needed to extend the curves, flow hydrographs for the years 1965, 1969 and 2001 were factored using a factor of 1.25. The results from the factored events combined with the historical period of record provide the annual peak discharge and stage data needed for the stage frequency analysis.

Stage Discharge for Cross-section just Downstream of Wisconsin River

In reaches of the river not influenced by tributary backwater effects (non-backwater reaches), a plot of the paired data has very little scatter about the spline rating curve. The absence of scatter is demonstrated in **Figure 5**, which represents cross-section 630.83, just downstream of the Wisconsin River.

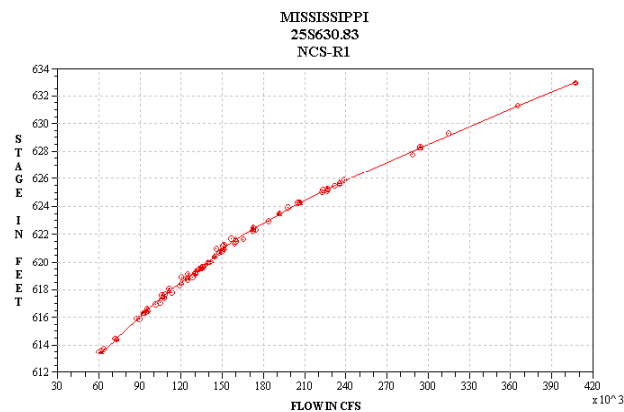


Figure 5. Comparison of paired annual maximum data and spline rating curve at cross-section 630.83 located just downstream of the Wisconsin River.

Stage Discharge for Cross-section just Upstream of Wisconsin River

In reaches influenced by tributary backwater effects (backwater reaches), a plot of the paired data shows more scatter about the spline rating curve. This is demonstrated in **Figure 6**, which represents cross-section 631.26, just upstream of the Wisconsin River. The scatter reflects the fact that the river stage in the backwater reach of a tributary is not simply a function of the upstream river discharge. Rather, it is dependent upon the river discharge upstream of the tributary and the river stage just downstream of the tributary. Since the stage in the backwater reach is a function of two variables, a family of rating curves is necessary to truly define the stage-discharge relationship. Because backwater reach rating curves generated by the rating_curve.exe program are only a function of the discharge upstream of the tributary, the stage obtained from the rating is correct only if the flow relationship between the Wisconsin River and the Mississippi River for the period of record analysis is preserved when the stage frequency analysis is accomplished. Otherwise, an unrealistic jump in the flood profile can occur across the tributary.

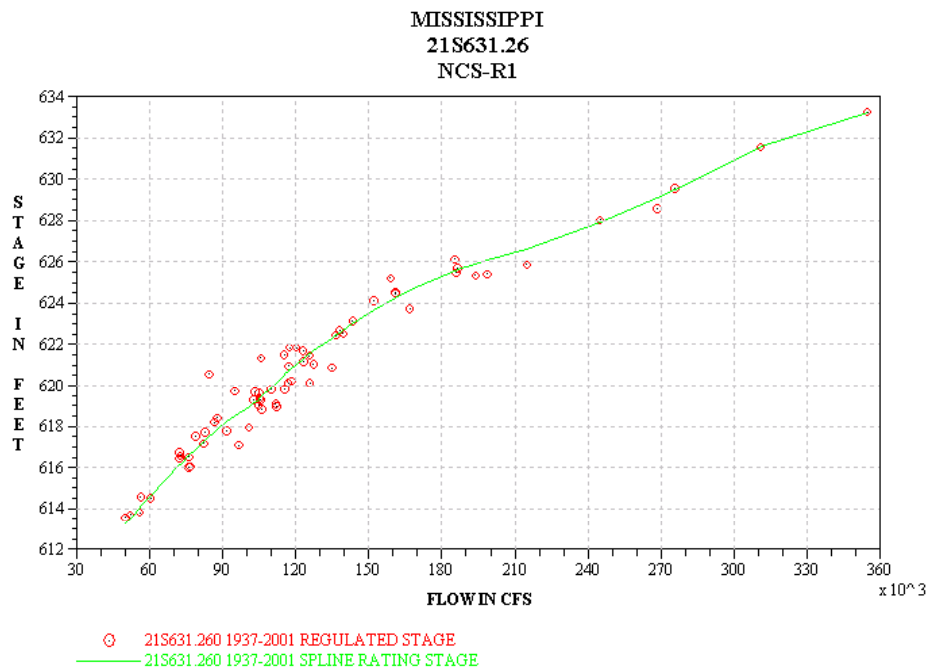


Figure 6. Comparison of paired annual maximum data and spline rating curve at cross-section 631.26, just upstream of the Wisconsin River.

Stage Frequency Software

The Flow Frequency Study stage-frequency programs [unetdss.exe, rating_curve.exe, regvsunreg.exe, area_vs_stats.exe, interpolate_stats.exe and stage_freq.exe] are used to process the UNET annual maximum data. for calculating the 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, 200-yr, and 500-year discharge and stage profiles. First, the

unetdss.exe program is run to pair the annual maximum discharge and stage data. Second, the rating_curve.exe program is run to rank the annual maximum discharge and stage data and produce a best-fit spline curve of the paired, ranked data. While the spline curve is typically referred to as a rating curve, it is, in essence, a curve relating the discharge and stage. Third, the area_vs_stats.exe or interpolate_stats.exe programs are used to interpolate statistics for each cross-section in the UNET model. Last, the stage_freq.exe program is used for computing the stage frequency elevations at each cross-section using the rating curve and statistics developed for each cross-section.

Discontinuity in Stage at the Wisconsin River

A Weibull annual exceedance stage probability plot of the UNET results for the Period or Record for River Mile 631.0 upstream and downstream of the Wisconsin River is shown below in **Figure 7**. As expected, the Weibull plots for the period of record do not show any difference in elevation for the sections immediately upstream and downstream of the Wisconsin River.

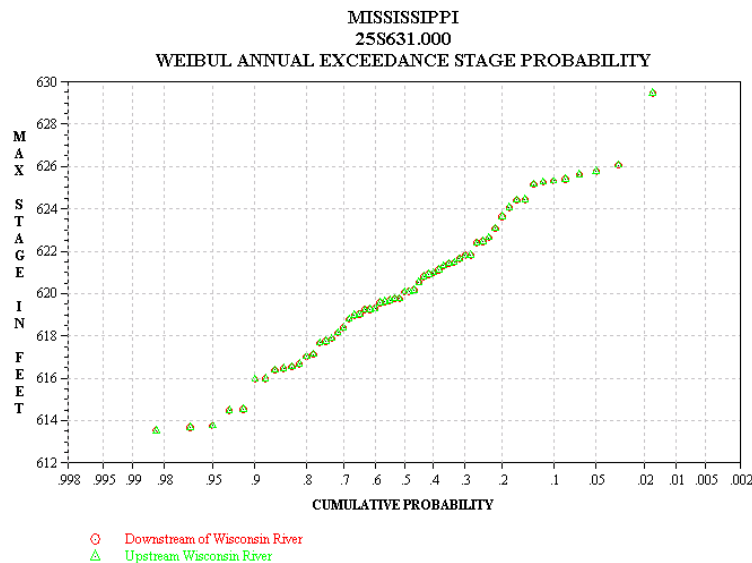


Figure 7. Wiebul Annual Exceedance Stage Probability for sections just upstream and downstream of the Wisconsin River.

Application of the stage frequency software for Mississippi River main stem discharge values across the Wisconsin River tributary using the drainage area statistics generated discontinuities in the computed water surface profiles. For the one percent chance flood event, the discontinuity or jump in the water surface profile is one foot for the Wisconsin River as shown in **Figure 8** below. Since the computed stage and discharge are one foot low at that location using the drainage area method, water surface elevations are impacted from that location to Dubuque, Iowa which is 52 miles downstream.

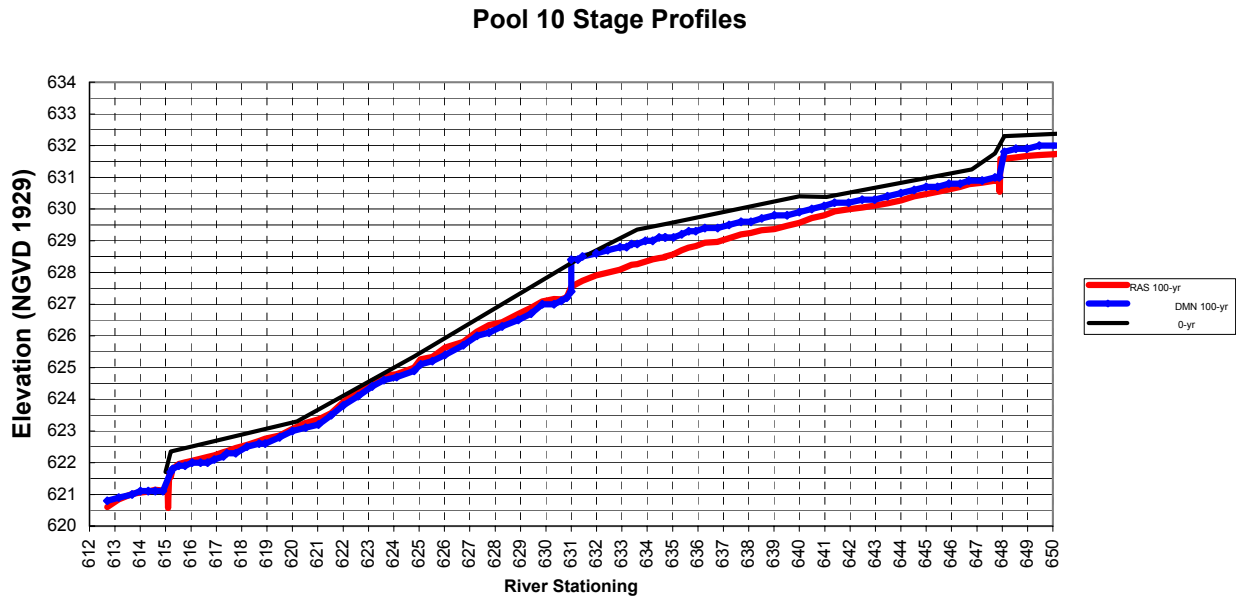


Figure 8. Illustration of the jump in the one percent chance flood profile generated at River Mile 631.0 using the Drainage Area Methodology.

Utilizing the general approach of determining flood distributions in between gages by a linear smoothing relationship of the mean flow and the standard deviation with drainage impacts the determination of stages upstream and downstream of the Wisconsin River. Coincident flows for the Wisconsin River in the UNET period of record simulation are not captured by the drainage area statistics at the main stem gages because of the excessive distance between those gages.

The general Flow Frequency Study methodology requires the development of rating curves at each section based on the annual maximum peak stage and flow values. This procedure generates curves which are dependent on the observed coincident flows from the Wisconsin River. **Figure 9** shows the relationship between the Mississippi River flow downstream of the Wisconsin River versus the flow upstream of the Wisconsin River at McGregor. The values determined by the drainage area approach are considerably lower than the values determined based on the UNET statistics. For this study, the results from the UNET period of record runs serve as a basis for determining the statistics downstream of the Wisconsin River. **Figure 10** shows the Wisconsin River coincidental flow plotted as a function of the McGregor flow. This plot also shows that the contribution from the Wisconsin River is much less using the drainage area approach in comparison to the contribution based on the UNET statistics.

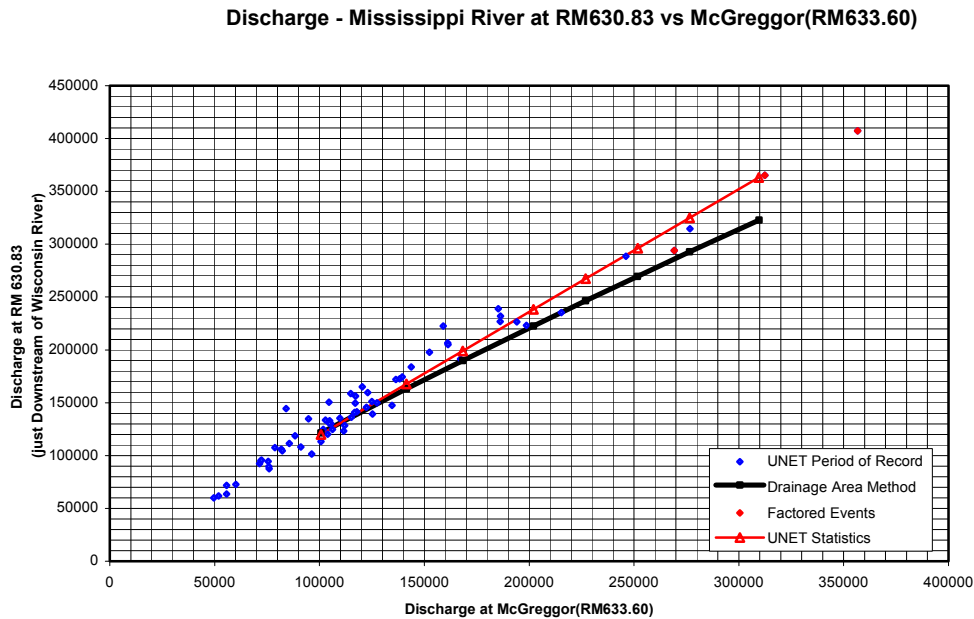


Figure 9. UNET Annual Peak Discharge at McGregor versus RM630.8 located just downstream of the Junction of the Mississippi River and Wisconsin River.

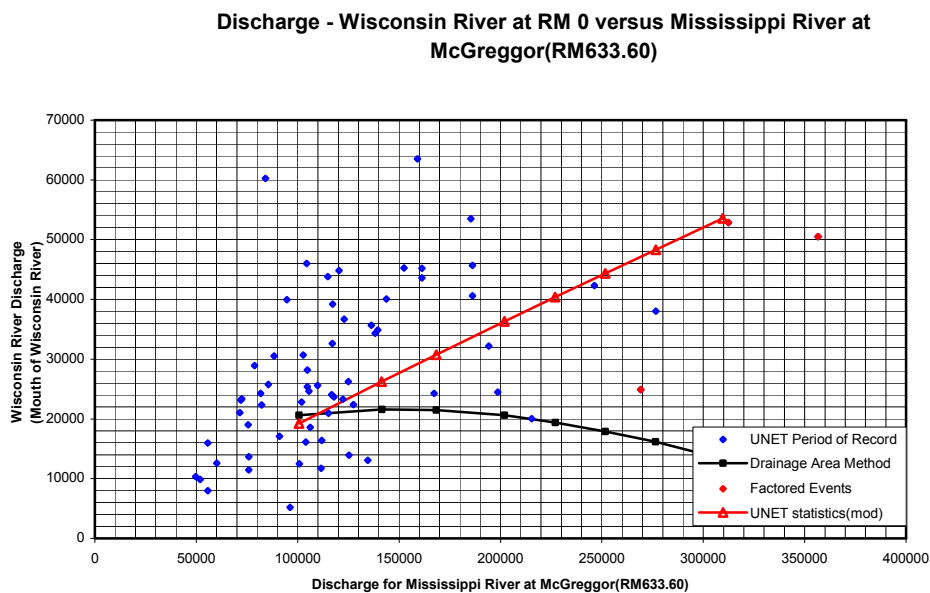


Figure 10. Discharge for Wisconsin River versus Peak Discharge for the Mississippi River at McGregor (River Mile 633.6).

Wisconsin River Confluence

The discharge profiles initially used drainage area relationships between USGS and COE gages for determining the appropriate discharges between these gages for development of

the final water surface profiles. The final interpretation of water surface profiles is for determining the water surface elevations from elevation-discharge rating curves developed at each cross section. This procedure worked well in most reaches, but resulted in jumps in the water surface profiles at certain locations where coincident flows from larger tributaries are not appropriately described by the drainage area relationships. The Wisconsin River confluence is one of these locations. The timing of larger floods required an adjustment at the mouth of the Wisconsin River due to the greater influence it has on peak discharges in the reach below the McGregor, Iowa. gage. This influence is not captured by the next downstream main stem gage at Dubuque in the main stem frequency analysis due to attenuation in this reach. This required the adjustment of the statistics at this location using the statistics from the UNET model for the shorter concurrent records analyzed at McGregor (RM 633.6) and the cross section just downstream of the confluence of the Mississippi River and Wisconsin River (RM 630.8).

The UNET statistics are used to weight the regionalized statistics between the McGregor and Dubuque Gages. The weighting is used for determining the appropriate adjustment in the statistics at River Mile 630.8 that is necessary to reflect the higher coincident flows needed for eliminating the discontinuity in the water surface profiles resulting from the drainage area interpolation procedure at this location. The following table reflects the statistics used in this weighting procedure.

Table 3. Statistics for the Wisconsin River.

	STATION				
	(1898-1998)	(1940-1998)	(1940-1998)	(1940-1998)	(1898-1998)
	McGregor	McGregor	RM633.6	Rm630.8	Dubuque
	Regionalized Statistics	Instantaneous Peaks	Mean Daily Peaks	Mean Daily Peaks	Regionalized Statistics
	USGS	USGS	UNET	UNET	COE
Mean	5.000	5.0446	5.0513	5.1366	5.1000
Std. Dev	0.178	0.16	0.1545	0.1573	0.1530
Skew	0.1	-0.1016	-0.0154	-0.2518	0.1

The weighting procedure yielded adjusted statistics tabulated in the following table at River Mile 630.8.

Table 4. Adjusted Statistics for River Mile 630.8.

	(1940-1998)
	Rm630.8
	Adjusted Statistics
Mean	5.0759
Std. Dev	0.1756
Skew	-0.1

Table 5. Period of Record Concurrent Analysis

PERCENT CHANCE Exceedance	Period of Record 1940-1998 Concurrent Record Analysis		
	STATION		
	McGregor	RM633.6	Rm630.8
	COMPUTED Curves		
0.2	306000	311000	341000
0.5	276000	280000	314000
1	254000	256000	294000
2	231000	233000	272000
5	201000	202000	241000
10	177000	177000	215000
20	151000	152000	187000
50	111000	113000	139000
80	81400	83400	102000
90	68800	71300	85200
95	59800	62600	73300
99	45800	49000	54500

Table 6. Instantaneous and Mean Daily Discharges for the Wisconsin River at McGregor and at River Mile 630.8 which is located just downstream of the Wisconsin River.

Year	McGregor	RM633.6	RM630.8	Year	McGregor	RM633.6	RM630.8
	Inst. Peaks USGS	McGregor Mean Daily Peaks-UNET	Wisc. River Mean Daily Peaks-UNET		Inst. Peaks USGS	McGregor Mean Daily Peaks-UNET	Wisc. River Mean Daily Peaks-UNET
1940	52100	55757	71729	1970	72100	72364	95693
1941	102800	101858	124682	1971	138000	136406	172065
1942	113800	117176	156386	1972	116000	114844	158640
1943	124600	124951	151207	1973	151000	159060	222557
1944	122500	122349	145625	1974	104000	103940	120072
1945	127700	138198	172504	1975	183000	186122	226745
1946	101200	104535	150541	1976	125000	120357	165167
1947	85500	85598	111356	1977	42000	49632	59980
1948	84000	81771	106024	1978	104000	105517	130165
1949	73100	75969	87438	1979	133000	134549	147621
1950	123300	125251	139173	1980	87400	88303	118842
1951	185700	186266	231935	1981	80700	82241	104601
1952	197500	198728	223212	1982	139000	139542	174407
1953	86200	91050	108147	1983	145000	152486	197724
1954	165500	167248	191534	1984	117000	117861	141551
1955	73700	71443	92476	1985	110000	109794	135395
1956	105000	104839	132999	1986	168000	161320	204936
1957	95800	96308	101508	1987	158000	161000	197200
1958	55800	55777	63738	1988	57200	60131	72708
1959	72300	72020	95177	1989	103000	111944	128329
1960	83100	84115	144381	1990	98800	106158	124733
1961	114000	127470	149871	1991	104000	104805	130179
1962	104000	102788	133478	1992	106000	115262	136227
1963	72000	75588	94584	1993	189000	185342	238839
1964	75600	75833	89514	1994	115000	116687	140748
1965	276000	276673	314722	1995	99600	100750	113253
1966	112000	117024	149616	1996	143000	143785	183842
1967	170000	161224	206444	1997	201000	194170	226375
1968	97900	94722	134664	1998	126000	122942	159636
1969	215000	215353	235364				

Comparison adjusted UNET statistics versus Drainage Area Statistics

A comparison of the one percent chance flood discharge profile from Dubuque, Iowa to McGregor, Iowa is shown in Figure 10 based on the results of the Drainage Area methodology versus the UNET statistics methodology.

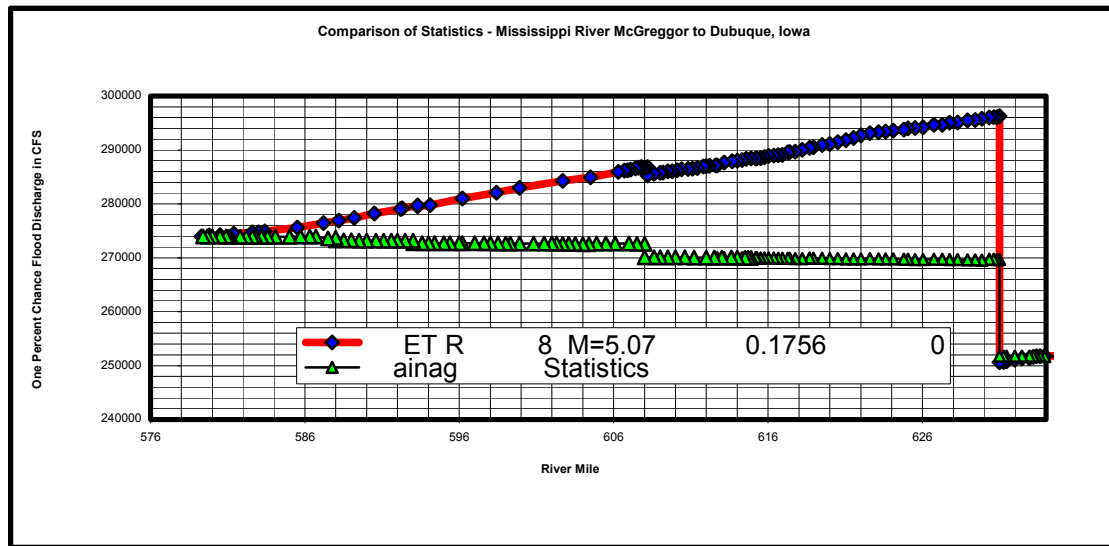


Figure 10. One percent chance discharge profiles for Drainage Area Methodology versus UNET statistics for the reach between McGregor and Dubuque, Iowa.

Annual peak floods statistics between McGregor and Dubuque, Iowa

A detailed discussion regarding the statistics for the flood profile between Dubuque and McGregor, Iowa is summarized in Dr. David Goldman's 24 April 2003 Memorandum for Record entitled, "Flood profile between McGregor and Dubuque." The following paragraphs summarizes conclusions from that memorandum.

The re-estimated statistics result in a flood profile where infrequent quantiles (e.g., the one percent chance flood peak annual discharge) decrease from McGregor to Dubuque despite the increase in drainage area. The decrease in flood quantiles seen between McGregor and Dubuque can be explained by the lack of coincidence between peaks occurring due to snowmelt upstream of River Mile 631 (the confluence with the Wisconsin River) and those for tributaries below this confluence. Note that the Turkey Creek, Grant and Platte Rivers, have flood peaks in March (presumably consisting of some snowmelt) and June (rainfall related floods). Peaks resulting from the Mississippi at or above the Wisconsin River confluence peak generally in April, missing these local tributary peaks. This is the most likely explanation for a decrease in flood quantiles despite the ten percent increase in drainage area from McGregor to Dubuque.

Flood peak statistics (the mean and standard deviation of the annual maximums) had been interpolated as a linear function of the drainage area. This is probably defensible upstream of McGregor and downstream of Dubuque where local inflows cause the expected increase of flood quantiles with drainage area. Note that the snowmelt floods occurring on the Minnesota, Wisconsin and Mississippi River at McGregor coincide in the month of April. Downstream of Clinton, spring floods from the Rock and Des Moines Rivers contribute significantly to the frequency of flooding on the Mississippi River at Keokuk. However, in the reach between McGregor and Dubuque, local flows are not coincident with the predominant flooding period at Dubuque in April. In this reach, interpolation using UNET period of record statistics is more appropriate because UNET captures the lack of coincidence in this reach.

Mississippi River Stage Frequency Water Surface.

From Mississippi River Mile 630.8 located just downstream of the Wisconsin River to Dubuque, Iowa, the St. Paul and Rock Island District's stage frequency analysis used the UNET statistics adjusted with anchor points at River Mile 630.8 and at Dubuque, Iowa. The resulting one percent chance flood profile is about one foot higher at Mississippi River Mile 630.8 thereby eliminating the jump in the profile at that location.

Conclusions

The annual maximum peak flow results from the UNET period of record simulations can provide a means for determining the coincidental flow from tributaries provided that the UNET model is optimized with regard to flow. The LATQ feature in the Graphical User Interface of the version of UNET used for the flow frequency study allows for the optimization of flow. In the case of the St. Paul Districts UNET model, flow is calibrated at the USGS gaging station at McGregor, Iowa upstream of the Wisconsin River and at the Dubuque, Iowa gage. For Dubuque, the stage hydrograph at the Lock and Dam No.11 Tailwater is used with the stage-discharge rating curve for that location for generating observed discharge hydrographs for the period of record. With the observed flow hydrographs for the Mississippi River at McGregor, Iowa and Dubuque, Iowa, the Wisconsin River at Muscoda, Wisconsin, the Grant River at Burton, Wisconsin and the Turkey River at Garber, Iowa, the LATQ feature of UNET optimized the ungaged local inflow allowing for the determination of flow hydrographs at locations in between the major gaging stations.

Assuring that the coincidental tributary flow is determined adequately minimizes the magnitude of discontinuities in the water surface profile when using the UNET period of record results in combination with the Flow Frequency Study stage frequency software.

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